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Sea ice observation in Antarctica
Status and Outlook

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Abstract (ca. 200 words):

There are known deficiencies in contemporary sea ice observation techniques. Manual methods are physically laborious and subject to human-induced observation error, as are ship-based methods. Upward Looking Sonar (ULS) allows the subsurface mapping of ice floe topography, though it is subject to acoustic propagation errors. Electromagnetic Induction Sounding (EM) is principally impaired by device size, weight and flight height. Visible/near-IR (VIR), thermal infrared (TIR) and laser altimetry are challenged by atmospheric interference and/or require solar illumination, limiting their applicability at night or in the polar winter. Microwave methods (Radar Altimetry, Passive Microwave) can penetrate cloud and snow cover, albeit at lower spatial and temporal resolutions. This paper provides a summary of current observation technology, and highlights future research directions in this field.

SEA ICE OBSERVATION IN ANTARCTICA

STATUS AND OUTLOOK

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ABSTRACT

There are known deficiencies in contemporary sea ice observation techniques. Manual methods are physically laborious and subject to human-induced observation error, as are ship-based methods. Upward Looking Sonar (ULS) allows the subsurface mapping of ice floe topography, though it is subject to acoustic propagation errors. Electromagnetic Induction Sounding (EM) is principally impaired by device size, weight and flight height. Visible/near-IR (VIR), thermal infrared (TIR) and laser altimetry are challenged by atmospheric interference and/or require solar illumination, limiting their applicability at night or in the polar winter. Microwave methods (Radar Altimetry, Passive Microwave) can penetrate cloud and snow cover, albeit at lower spatial and temporal resolutions. This paper provides a summary of current observation technology, and highlights future research directions in this field.

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INTRODUCTION

Sea ice plays an important role in the global climate system, contributing to the surface albedo of the Earth (Brandt et al., 2005) and reflecting a large portion of incoming shortwave solar radiation (Maykut, 1986). Sea ice also provides a physical barrier between ocean and air, while regulating heat exchange between ocean and atmosphere through low thermal conductivity (Schwerdtfeger, 1963). Sea ice has ecological significance for resident microbial life (Lizotte, 2001) in addition to marine ecosystems along continental ice shelves (Tynan, 1998), while the subsurface topography of sea ice provides a substrate for submerged ecosystems such as algae and other primary producers (Wadhams, 2012).

Antarctic sea ice is seasonal (Rees, 2005), covering approximately 8% of the Southern Hemisphere (Lubin & Massom, 2006) during maximal extent (September) and can extend approximately 40% of the Southern Ocean (Lizotte, 2001). Because of this, sea ice presents logistical challenges for polar vessels, both government and commercial (Mastny, 2000). Irrespective of application, the study and observation of sea ice is of particular interest to researchers and logisticians, stimulating continued research and development in the field.

Observations of sea ice originate from early polar expeditions, through the diary entries of explorers as they journeyed through pack ice to reach the Antarctic continent (e.g. Scott's *Terra Nova* expedition). However, it was not until the 1970s (Breivik et al., 2009) and the advent of passive microwave platforms (e.g. Nimbus-7 [US]) that technology matured to a point that enabled comprehensive observation from space, irrespective of the cloud or daylight conditions that impaired the visible, near-IR, and infrared techniques in the years prior (Burns et al., 1992; Lubin & Massom, 2006; Rees, 2005).

The Antarctic Sea Ice Processes and Climate (ASPeCt) expert group was established in 1996 by the Scientific Committee on Antarctic Research (SCAR) Physical Sciences Group to further the understanding of sea ice, with a particular emphasis on observation (Australian Antarctic Division, 2013). By formulating comprehensive guidelines and standards for the capture of sea ice information, the group formalized the processes of sea ice observation with regards to a myriad of physical attributes. This paper will synthesise the principle techniques in use today for a subset of these attributes: extent and concentration, thickness, morphology and topography.

SEA ICE EXTENT AND CONCENTRATION

Sea ice extent refers to the amount of sea ice coverage of the ocean and is formed as a result of freezing waters in the Polar Regions. The term "extent" is often used interchangeably with "concentration", which instead refers to the amount of sea ice coverage within a given target area (Worby et al., 1999).

SEA ICE THICKNESS

Sea ice thickness is function of seasonal snow accumulation, melt, deformation, and floe convergence (Lemke et al., 2007). Thickness information is essential in the calculation of total ice volume for a variety of scientific applications (such as quantifying ocean-atmosphere interactions), as well as the planning of exercises on the ice itself (Breivik et al., 2009).

SEA ICE MORPHOLOGY AND TOPOGRAPHY

Sea ice morphology is described in terms of *freeboard* (the ice above the water line) and *draft* (the ice below the water line). These features can be observed on a topographical scale to determine the convergence of independent ice fields through the formation of pressure ridges, ridge sails, and keels (Haas, 1998), as illustrated in Figure 1.

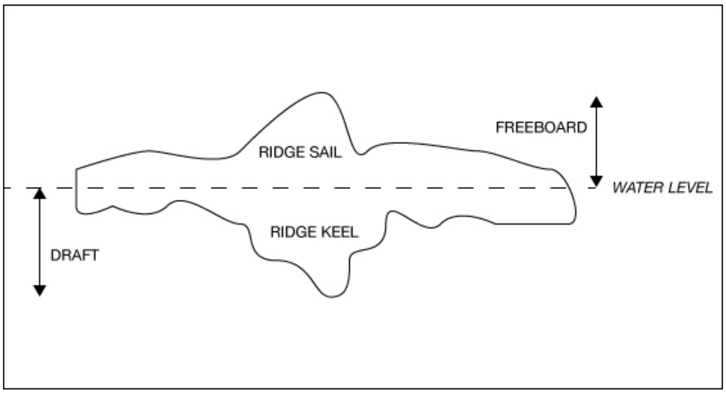

Figure 1 - Physical sea ice morphology: freeboard, draft, ridge sail and ridge keel

The study of sea ice undersea topography has remedial and logistical application in calculating the containment potential of oil spills, as well as the design and navigation of ice-breaking vessels (Melling et al., 1995; Wadhams, 2012). Sea ice topography is intrinsic to the study of sea ice behaviour, particular that of the discrimination between first year (FY) and multi-year (MY) ice.

MANUAL METHODS

Manual and historical methods of sea ice extent/concentration observation are still commonly used: either *in-situ*, aboard icebreaking vessels or passing aircraft. Worby et al. (1999) describe a simplistic approach to measuring ice extent/concentration as a visual observation of the target area, expressed in integer "tenths". Table 1 shows a sample of the designations used in the field:

Table 1 - Sample sea ice designations from visual observation. Adapted from Worby et al. 1999.

Designation	Description
0	Complete coverage, no openings
10	Near-complete coverage (95%-99%, small cracks)
...	...
1	Open water

In order to reduce (but not eliminate) any bias from human-induced observation error, the implementation guidelines for the ASPeCt protocol detail standard execution and data format practices for observations of this form (Worby et al., 1999). The practice of making observations is encouraged (though not enforced) for all vessels entering pack ice in the region.

Sea ice thickness can be derived through point drilling exercises whereby a manual or mechanical drill is used to physically measure the distance the drill must travel to either transect the ice completely (in the case of thin ice) or reach the water line, thus exposing the *freeboard height*. Once the freeboard has been exposed, the Archimedes buoyancy principle can be used to estimate sea ice thickness (Yi & Zwally, 2010):

$$T = \frac{\rho_w}{\rho_w - \rho_i} F \frac{\rho_w - \rho_s}{\rho_w - \rho_i} T_s$$

where T is sea ice thickness, F is freeboard height, T_s is snow depth, ρ_w is water density, ρ_s is snow density, and ρ_i is sea ice density. This approach to thickness calculation assumes hydrostatic equilibrium of the ice, as well as known snow cover and water/sea-ice density.

Deriving the density of sea ice can be problematic due to pockets of brine or air (Rees, 2005), as well as biological matter and other impurities. The concentrations of these pockets vary between ice volumes as well as changing as the ice ages, in particular the amount of brine which is rejected and expelled over time (Rees, 2005). Manual snow accumulation observations are typically made with the use of snow stakes, a subdivided pole with fixed measurement markings that can be inserted into the ice/snow to measure snow accumulation over time.

In practice, ice transects are drilled in a line or gridded pattern with equal spacing to derive a thickness profile or field, yielding a thickness distribution and (potentially) insight into the subsurface topography. Wagner (2009) describes the technique as physically cumbersome and yielding of little data over a large area, necessitating automated methods as a preferred approach. Irrespective of this, manual point drilling profiles are still widely used as a ground-truth measurement and validation technique for other remote sensing techniques.

SHIP-BASED METHODS

Ship-based observations are a classification of readings made by vessels passing through pack ice, producing an increasingly dense dataset as polar activity increases (Eicken & Salganek, 2010, p. 379). Worby et al. (1999) and Toyota (2009) describe the primary methods for taking ice thickness measurements from a ship as visual observation and video-recorded observation. These methods are principally equivalent whereby a measurement gauge or “yardstick” is visually compared with ice floe thickness as breaking ice overturns along the hull of the ship and the approximate thickness recorded.

These methods perform best with regular, stratiform ice with the measured edge parallel to the water (Wagner, 2009), as breakaway ice of this form is more easily overturned than its irregularly shaped counterpart (Toyota, 2009). There is known bias to these methods, as shipping passages are typically selected for the thinnest and most direct route (Xie et al., 2013) in the interest of time and fuel conservation as opposed to comprehensive data coverage. Again, there are guidelines for vessels entering the pack ice, detailing both the technical execution and the standardized format of observations (Worby et al., 1999).

SONAR METHODS

Sonar methods observe sea ice thickness and subsurface topography from below by using sonar depth information. Toyota (2009) describes two methods of sonar profiling: submarine sonar profiling, and moored ice profiling sonar. Both methods operate by using an upward-looking sonar (ULS) beam to determine distance to ice bottom (draft) from the source, subtracting the depth to acquire thickness information. Submarine methods capture a profile of readings as the device proceeds along a path beneath, whereas the moored method profiles the ice floe (or floes) immediately above the *in-situ* device fixed to the sea floor.

Submarine ULS offers greater spatial coverage at the expense of lower temporal resolution (restricted to when vessels were passing through) and a lower relative accuracy of ±0.3m (Wadhams & Horne, 1980) compared to ±0.05m-0.1m of the moored method (Melling et al., 1995). Moored methods have greater applicability in shallow continental waters (Toyota, 2009) where submarines simply cannot operate and can provide continuous time series data for multiple seasons or years (Renner & Lytle, 2007). Moored methods also have the ability to observe multiple passing floes as well as tracking floe evolution over time (Melling et al., 1995).

Both methods are subject to under-ice acoustic propagation issues as a result of the irregular undersea topography of ice drafts (Wadhams, 2012), as well as the sparse distribution of data coverage overall (Strass & Fahrbach, 1998).

Recently, the use of Autonomous Underwater Vehicles (AUV) with ULS (e.g. Wadhams, 2012; Williams et al., 2014) has allowed for greater coverage for selected ice fields and for the visual discrimination between First Year (FY) and Multi-Year (MY) ice; whereby the presence of "rugged undersides" (as a result of uneven melting from previous summers) indicates the presence of MY ice (Wadhams, 2012).

ELECTROMAGNETIC INDUCTION SOUNDING

Electromagnetic Induction Sounding (EM) is a technique of sea ice observation that uses electromagnetic induction to measure the apparent ground conductivity of sea ice (Kovacs & Morey, 1991). EM is often used in conjunction with other methods to establish mean thickness (such as with point drilling), or to validate remotely sensed observations such as satellite or passive microwave (Haas, 1998).

EM involves the induction of an eddy current from a transmission coil into the sea water below the ice, this eddy current produces a secondary current which is sensed by the receiver coil where it is converted into a distance calculation of the water level from the instrument (Haas, 1998; Uto et al., 2006). EM exploits a physical property that renders sea ice relatively transparent at the EM operating frequency of 9.8kHz (Kovacs & Morey, 1991) and is typically paired with a laser altimeter to correct for height fluctuations during continuous observation.

Kovacs et al. (1987) note that the effective footprint of the device is two to three times the device height above the seawater. As such, the calculated thickness reported at a specified height is an assumed average for the footprint area below. In the case of suitably deformed ice, this causes discrepancy with point drilling measurements and is one of the principle criticisms of the technique. This is further exacerbated by a reduction in device sensitivity and effective resolution as device height increases (Haas, 1998), despite the application of EM at heights of 20-30m in aerial sounding exercises. Arguably flying the device closer to the ice is preferable, however this is somewhat prohibited by the current size and weight of these devices, which necessitates helicopter airlift.

Another criticism of the technique is its propensity for error due to melt or saltwater pooling on particularly deformed ice (Haas, 1998), whereby the change in apparent conductivity may underestimate floe thickness. For the same reasons the technique is also known to be unreliable at flow edges where the device footprint covers both ice and clear water. EM is also most reliable with uniform thickness ice, whereas the presence of ridged ice (with seawater cavities) can degrade performance up to 30% (Toyota, 2009). Haas (1998) notes that EM methods are unreliable at reporting the thickness of snow-covered ice, as the EM technique alone cannot distinguish between ice and snow and often overestimates thickness in such cases.

The technique neglects to consider the influence of the vehicle it is attached to, such as an icebreaking ship. In this scenario, cracked or fractured ice may interfere with either the laser altimeter (affecting height correction), or introduce clear water gaps or pooling below the instrument itself, again underestimating floe thickness (Haas, 1998). Despite this, the spatiotemporal collocation of validation data (i.e. ship-based methods) to the EM sounding presents a convenient proposition to further the technology.

The benefits of EM lie in its applicability to a variety of observation exercises, as EM devices may be handheld, positioned *in-situ*, or affixed to vehicles. Aerial application presents lower risk to the operator (where thinner ice may be hazardous) as well as access to isolated ice fields that are otherwise inaccessible by other means (largely due to the size and weight of the device). However, there is an added environmental and financial cost in the form of additional fuel usage, which may be partly responsible for the slow adoption of the EM technique on a larger scale.

VISIBLE/NEAR-INFRARED METHODS

Sea ice has been observed from space using the visible, infrared and microwave portions of the electromagnetic spectrum since the 1970s (Xie et al., 2013). Sea ice in various stages of development can be observed in the visible and near-IR (VIR) portion of the electromagnetic spectrum (see Rees, 2005, p. 124), albeit with difficulty at certain wavelengths (0.4µm - 1.3µm) where water and ice share similar optical properties (Dozier, 1989). VIR sensor platforms are also typically calibrated for a fixed number of wavelength channels, leaving sea ice extent to be derived algorithmically as a function of other, more general-purpose wavelengths (i.e. Schmit et al., 2005).

In practice, sea ice extent can be determined algorithmically using reflectance, absorbance, or albedo, and is varied between agencies and sensor platforms. For example, Wagner (2009) lists some useful albedo classifications for automated water/ice discrimination as: open water (0.05), ponded ice (0.2-0.4), bare ice (0.5-0.7), and snow-covered ice (0.75-0.85). Sea ice thickness can also be derived as a function of albedo (Rees, 2005), however, this relationship largely breaks down beyond a certain thickness value (~0.3m) or when even a thin layer of snow is present (Allison, 1997). Consequently, VIR imagery and albedo information are seldom used to derive thickness information.

The prevailing criticism of VIR techniques is the inability to penetrate or delineate optically thick cloud cover (Burns et al., 1992; Lubin & Massom, 2006; Rees, 2005). VIR also requires solar illumination, limiting applicability for night and the polar winter (Lubin & Massom, 2006). Despite these caveats, VIR imagery is of significantly higher spatial and temporal resolution than other methods (e.g. Passive Microwave), and is still preferable where available.

THERMAL INFRARED METHODS

Thermal Infrared (TIR) Methods of satellite observation operate in the TIR region of the electromagnetic spectrum (3μm-14μm) (Lubin & Massom, 2006). Though still impeded by cloud cover, TIR provides the ability to observe sea ice extent/concentration at night, particularly at the 8μm-14μm waveband (where the contribution of solar reflectance is lower) (Stewart, 1985). Rees (2005) describes the thermal infrared properties of sea ice as being similar to that of freshwater ice, in particular an emissivity characteristic of approximately 0.98. To date, there are no reliable methods to discern sea ice thickness from the TIR method.

PASSIVE MICROWAVE METHODS

Passive Microwave (PMW) data has been available for use in sea ice extent/concentration analysis since the 1970s (Toyota, 2009), and has been considered the "workhorse" of sea ice observation since that time in both the Arctic and Antarctic (Breivik et al., 2009; Lubin & Massom, 2006). By operating in the microwave portion of the electromagnetic spectrum (1mm-1m), PMW surpasses VIR and TIR in its ability to operate in both day and night, and to penetrate cloud cover (Toyota, 2009). PMW exploits the high emissivity of sea ice (~0.98) as compared to open water (Rees, 2005; Toyota, 2009), with relatively high accuracy and areal coverage. PMW boasts a near continuous time series since 1978 (Lubin & Massom, 2006) and, due to low spatial resolution, daily scenes are often available. However, present day PMW sensors are restricted to Low Earth Orbit (LEO), Polar-Orbiting satellites, which results in low temporal resolution to perhaps one or two scenes per day (Scofield, 1987).

As information captured by the sensor comes from the top few centimetres of the Earths surface (Toyota, 2009), it is difficult to discern a sea ice thickness value directly. There have been studies into the effects of brine exclusion (which is correlated to thickness) and its effect on the dielectric properties of sea ice (Kovacs, 1996; Vant et al., 1978), which does have PMW observation potential. PMW is also sensitive to melt water/pooling conditions, and thin, snow-free ice (<0.3m) is nearly indistinguishable from open water at the operating frequencies of PMW.

ALTIMETRY

Altimetry covers a class of observation that measures sea ice freeboard height with reference to the local ellipsoid (sea level), and is commonly derived through one of two mechanisms: laser profiling, and radar altimetry (Toyota, 2009). Once the freeboard height is established, the Archimedes buoyancy principle can again be invoked to calculate ice thickness once sea height is subtracted from the recorded elevation (Laxon et al., 2003).

Aerial and space-borne laser profiling operates by emitting and receiving light pulses in regular intervals to profile the surface elevation immediately below the instrument (Farrell et al., 2011;

Kwok & Cunningham, 2008). Laser altimetry is subject to cloud interference, as well as the inability to discern snow accumulation from true freeboard height (Kwok & Cunningham, 2008).

Radar altimetry operates by beaming radio waves towards the surface of the earth, discerning elevations from the radar echo reported by the instrument (Rees, 2005), albeit at lower spatial resolution. However, the ability to penetrate cloud cover positions radar altimetry as the preferred approach for space-borne freeboard observation.

CONCLUSION

Several strengths and weaknesses have been identified for contemporary sea ice observation techniques. Manual methods are physically demanding and subject to human-induced observation error, though protocols such as ASPeCt aim to reduce any bias through guidelines and standards, especially for vessels entering the pack ice. The risks to personnel and equipment suggest that the further use of Autonomous Underwater Vehicles (AUV) or Unmanned Aerial Vehicles (UAV) should be considered to overcome the known insufficiencies of the various techniques, especially in the case of Electromagnetic Induction Sounding (EM) where lower altitudes will increase measurement accuracy. Day/night conditions and atmospheric interference continue to impair VIR, TIR, and laser altimetry methods. However, the comparably higher spatial and temporal resolution to their microwave counterparts argue for continued use where daytime and clear sky conditions are available.

In general, the state of sea ice observation is promising. Researchers today have unprecedented coverage and accuracy through technology, allowing comprehensive observation in almost all conditions. Through continued development and refinement of tools and techniques discussed known deficiencies can be addressed to further our understanding sea ice.

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REFERENCES

Allison, I. (1997). Physical processes determining the Antarctic sea ice environment. *Australian Journal of Physics, 50*(4), 759-772.

Australian Antarctic Division. (2013). *Overview of ASPeCt.* Retrieved from http://aspect.antarctica.gov.au/. Accessed 4 December 2014

Brandt, R. E., Warren, S. G., Worby, A. P., & Grenfell, T. C. (2005). Surface albedo of the Antarctic sea ice zone. *Journal of Climate, 18*(17), 3606-3622.

Breivik, L. A., Carrieres, T., Eastwood, S., Fleming, A., Girard-Ardhuin, F., Karvonen, J., . . . Tonboe, R. (2009). *Remote Sensing of Sea Ice.* Paper presented at the OceanObs'09: Sustained Ocean Observations and Information for Society, Venice, Italy.

Burns, B. A., Schmidt-Grottrup, M., & Viehoff, T. (1992). Methods for digital analysis of AVHRR sea ice images. *Geoscience and Remote Sensing, IEEE Transactions on, 30*(3), 589-602.

Dozier, J. (1989). Remote sensing of snow in visible and near-infrared wavelengths (pp. 527-547): John Wiley and Sons: New York.

Eicken, H., & Salganek, M. (2010). *Field Techniques for Sea-Ice Research*. Fairbanks, Alaska, USA: University of Alaska Press.

Farrell, S. L., Markus, T., Kwok, R., & Connor, L. (2011). Laser altimetry sampling strategies over sea ice. *Annals of Glaciology, 52*(57), 69-76.

Haas, C. (1998). Evaluation of ship-based electromagnetic-inductive thickness measurements of summer sea-ice in the Bellingshausen and Amundsen Seas, Antarctica. *Cold Regions Science and Technology, 27*(1), 1-16. doi: http://dx.doi.org/10.1016/S0165-232X(97)00019-0

Kovacs, A. (1996). Sea ice. Part 1. Bulk salinity versus ice floe thickness: DTIC Document.

Kovacs, A., & Morey, R. M. (1991). *Sounding sea ice thickness using a portable electromagnetic induction instrument.* Paper presented at the Proceedings - International Conference on Port and Ocean Engineering Under Arctic Conditions, POAC.

Kovacs, A., Morey, R. M., & Cox, G. F. N. (1987). Modeling the electromagnetic property trends in sea ice, part I. *Cold Regions Science and Technology, 14*(3), 207-235. doi: http://dx.doi.org/10.1016/0165-232X(87)90015-2

Kwok, R., & Cunningham, G. F. (2008). ICESat over Arctic sea ice: Estimation of snow depth and ice thickness. *Journal of Geophysical Research: Oceans, 113*(8).

Laxon, S., Peacock, N., & Smith, D. (2003). High interannual variability of sea ice thickness in the Arctic region. *Nature, 425*(6961), 947-950.

Lemke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., . . . Thomas, R. H. (2007). Observations: Changes in snow, ice and frozen ground. *Titel: Climate change 2007: the physical science basis; summary for policymakers, technical summary and frequently asked questions. Part of the Working Group I contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 337-383.

Lizotte, M. P. (2001). The contributions of sea ice algae to Antarctic marine primary production. *American zoologist, 41*(1), 57-73.

Lubin, D., & Massom, R. (2006). *Polar Remote Sensing: Volume I: Atmosphere and Oceans* (Vol. 1): Springer.

Mastny, L. (2000). Melting of earth's ice cover reaches new high. *Worldwatch News Brief, 6*.

Maykut, G. A. (1986). *The surface heat and mass balance*: Springer.

Melling, H., Johnston, P. H., & Riedel, D. A. (1995). Measurements of the Underside Topography of Sea Ice by Moored Subsea Sonar. *Journal of Atmospheric and Oceanic Technology, 12*(3), 589-602. doi: 10.1175/1520-0426(1995)012<0589:MOTUTO>2.0.CO;2

Rees, W. G. (2005). *Remote sensing of snow and ice*: CRC Press.

Renner, A. H. H., & Lytle, V. (2007). Sea-ice thickness in the Weddell Sea, Antarctica: a comparison of model and upward-looking sonar data. *Annals of Glaciology, 46*(1), 419-427. doi: 10.3189/172756407782871350

Schmit, T. J., Gunshor, M. M., Menzel, W. P., Gurka, J. J., Li, J., & Bachmeier, A. S. (2005). Introducing the next-generation Advanced Baseline Imager on GOES-R. *Bulletin of the American Meteorological Society, 86*(8), 1079-1096.

Schwerdtfeger, P. (1963). The thermal properties of sea ice. *J. Glaciol, 4*(36), 789-807.

Scofield, R. A. (1987). The NESDIS operational convective precipitation-estimation technique. *Monthly Weather Review, 115*(8), 1773-1793.

Stewart, R. H. (1985). Methods of satellite oceanography.

Strass, V. H., & Fahrbach, E. (1998). *Temporal and regional variation of sea ice draft and coverage in the Weddell Sea obtained from upward looking sonars*: Wiley Online Library.

Toyota, T. (2009). Application of Remote Sensing to the Estimation of Sea Ice Thickness Distribution. In G. Jedlovec (Ed.), *Advances in Geoscience and Remote Sensing* (pp. 21-44). Rijeka, Croatia: InTech.

Tynan, C. T. (1998). Ecological importance of the southern boundary of the Antarctic Circumpolar Current. *Nature, 392*(6677), 708-710.

Uto, S., Toyota, T., Shimoda, H., Tateyama, K., & Shirasawa, K. (2006). Ship-borne electromagnetic induction sounding of sea-ice thickness in the southern Sea of Okhotsk. *Annals of Glaciology, 44*(1), 253-260. doi: 10.3189/172756406781811510

Vant, M., Ramseier, R., & Makios, V. (1978). The complex ‐ dielectric constant of sea ice at frequencies in the range 0.1–40 GHz. *Journal of Applied Physics, 49*(3), 1264-1280.

Wadhams, P. (2012). The use of autonomous underwater vehicles to map the variability of under-ice topography. *Ocean Dynamics, 62*(3), 439-447.

Wadhams, P., & Horne, R. (1980). An analysis of ice profiles obtained by submarine sonar in the Beaufort Sea. *Journal of Glaciology, 25*, 401-424.

Wagner, P. (2009). *Intercomparisons of sea ice thickness and concentration from visual observation, EM-31 measurements, and video imagery.* Dissertation/Thesis, ProQuest, UMI Dissertations Publishing.

Williams, G., Maksym, T., Wilkinson, J., Kunz, C., Murphy, C., Kimball, P., & Singh, H. (2014). Thick and deformed Antarctic sea ice mapped with autonomous underwater vehicles. [Article]. *Nature Geosci, advance online publication*.

Worby, A. P., Allison, I., & Dirita, V. (1999). *A Technique for Making Ship-Based Observations of Antarctic Sea Ice Thickness and Characteristics*. Hobart, Tasmania, Australia: Antarctic CRC.

Xie, H., Tekeli, A. E., Ackley, S. F., Yi, D., & Zwally, H. J. (2013). Sea ice thickness estimations from ICESat altimetry over the Bellingshausen and Amundsen Seas, 2003–2009. *Journal of Geophysical Research: Oceans, 118*(5), 2438-2453.

Yi, D., & Zwally, J. H. (2010). *Arctic Sea Ice Freeboard and Thickness.* Retrieved from http://nsidc.org/data/docs/daac/nsidc0393_arctic_seaice_freeboard/. Accessed 1 December 2014